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COSTS OF PROVIDING EDIBLE BIOMASS FOR A BALANCED VEGETARIAN DIET IN A CONTROLLED ECOLOGICAL LIFE-SUPPORT SYSTEM[1]

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OPTIMISTIC, SIMPLIFIED ESTIMATES OF CROPPING AREA FOR CELSS

Various researchers have calculated cropping areas to provide oxygen, water, and food calories to support the human crew of a Controlled Ecological Life-Support System (CELSS) to be deployed in space without resupply from Earth (Hoff *et al.* 1982, Mitchell 1993, Salisbury and Bugbee 1985, Tibbitts and Alford 1982). Most are optimistic calculations based upon the highest yield and productivity rates achieved to date for a single crop, usually under modified controlled environments and hydroponic culture. For example, it has been estimated that 13 m^2 of closed wheat canopy growing under intensive cultivation conditions in a controlled environment could provide the food calories needed to sustain a person (Salisbury 1991). The oxygen required by a person has been produced by 20 m^2 of wheat growing under less intensive conditions in the materially closed Biomass Production Chamber (BPC) at the Kennedy Space Center, while the drinking water requirement was met by only 3 m^2 of this wheat (Wheeler 1992). Similar calculations indicate that 25 m^2 of white potato canopy in a growth chamber could provide the nutritional calories (Wheeler and Tibbitts 1987), whereas 39 m^2 of sweetpotatoes growing hydroponically in a greenhouse could accomplish the same thing (Hill *et al.* 1989). The most optimistic calculations typically are based upon projected maximum yields for a single crop plus textbook values of calorie and oxygen requirements for a male person of body mass chosen by the researcher (Hoff *et al.* 1982).

CELSS OXYGEN IN EXCESS OF HUMAN RESPIRATORY REQUIREMENTS

In a closed, recycling life-support system, the molar amount of oxygen evolved during photosynthesis should be equivalent to the molar amount of carbon dioxide fixed:

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$$6CO_2 + 12H_2O \xrightarrow[\text{chlorophyll}]{400\text{–}700\text{ nm}} C_6H_{12}O_6 + 6O_2 + 6H_2O$$
(Devlin and Barker 1971)

Deviations of the Assimilatory Quotient (CO_2 fixed per O_2 released) from the ideal 1 : 1 ratio occur depending on oxidase, oxygenase, and peroxidase activities in plant tissues, as well as the rate of fat vs. carbohydrate or protein synthesis occurring at a given time (Rabinowitch 1945). In any case, the mass of oxygen produced during a cropping cycle will exceed the mass of edible biomass formed by an amount proportional to the non-edible biomass formed concomitantly (Wheeler *et al.* 1996). In a CELSS, the amount of oxygen released during photosynthesis that is proportional to carbon partitioned into edible crop biomass will be required to oxidize food to carbon dioxide and water in the human digestive system. The amount of photosynthetic oxygen related to non-edible crop biomass will be required to completely degrade cellulose, lignin, and other residue in the waste-processing unit of the space habitat. The bottom line for a CELSS crew is that producing enough crop biomass to satisfy their nutritional needs will automatically satisfy their oxygen requirement as well.

EXCESSIVE WATER PRODUCTION IN CELSS

The total crop area needed to meet a CELSS crew's food requirement could be much more than needed to satisfy the drinking water requirement. On a mass basis, from 100 to more than 200 times as much water was transpired than CO_2 was fixed by CELSS candidate crops growing in the closed BPC (Wheeler *et al.* 1996). The average transpiration/photosynthesis ratio for all crops tested was 128 g H_2O : 1 g CO_2 totaled over entire cropping cycles. A standard reference man typically needs about 2.5 liters water each day to satisfy his drinking water requirement (Hopkins 1993). On the other hand, a closed soybean canopy 1 m^2 in area transpires water vapor at an average rate of 4.3 liters (kg)$\cdot$day^{-1} in the BPC (Wheeler *et al.* 1996). Thus, only 0.58 m^2 of soybeans would be needed to satisfy the drinking water requirement for one person. However, water also will be required for cooking, washing, and sanitary purposes in CELSS. If the water-use rate is projected to 40 liters$\cdot$person$^{-1}\cdot$day^{-1} for all uses, then 9.3 m^2 of soybean canopy (or other equivalent CELSS crop) could do the job easily. Additional environmental manipulation may be required in a CELSS to suppress canopy transpiration without greatly compromising crop productivity. For example, water vapor efflux from foliage can be throttled up or down by changing ambient humidity, which affects the vapor pressure deficit between leaves and the air. Higher humidities lessen the driving force for transpirational water loss, whereas lower humidities steepen the gradient. Enrichment of atmospheric CO_2 also tends to suppress transpiration by reducing stomatal aperture and decreasing stomatal conductance to water vapor. Optimum combinations of high humidity, CO_2 enrichment, cool temperatures, and chemical antitranspirants may be needed to avoid excessive water cycling in closed systems.

ESTIMATING NUTRITIONAL ENERGY REQUIREMENTS FOR HUMANS IN CELSS

Since the crew of a space-deployed CELSS will be sustained for prolonged periods of time on a mainly vegetarian diet, it becomes imperative that the diet be balanced with respect to the major macronutrients (protein, fat, and carbohydrate), whose storage mass would become prohibitive for distant, long-duration space missions involving large crew sizes (MacElroy *et al.* 1985). The National Research Council (NRC) of the United States National Academy of Sciences recommends a 2900 kcal·day^{-1} diet for a modern reference man, who is 25 to 50 years old and weighs 79 kg (National Research Council 1989). However, the human oxygen requirement (McArdle *et al.* 1986), if converted to units of energy expenditure (about 5 kcal·liter O_2^{-1}), falls more than 900 kcal short of the NRC-recommended value for food-energy intake. At this rate of food intake vs. energy expenditure, a standard man (call him Al) would gain weight on a 2900 kcal·day^{-1} diet. One reason for this discrepancy is that the value 0.21 liters O_2·(kg body wt)$^{-1}$·h^{-1} has been used to calculate the respiratory rate of humans for estimates of food requirements (Schmidt-Nielsen 1983). However, exercise physiologists find this oxygen-consumption rate to represent an activity level slightly above sleeping on the human activity scale (Table 1). Rather, CELSS crew members likely will pursue an ambitious daily schedule of exploration and research on the lunar and martian surfaces. Office work and light exercise consume twice as much oxygen and energy as sleep, whereas heavy exercise utilizes more than 4 times as much of each. Reasonable time windows were assigned to a range of activities with an ambitious planetary exploration schedule in mind. Based on this schedule, about 712 liters (28 moles) of O_2 are required per person per day, compared to the 400 liters (16 moles) calculated from estimated caloric requirements for a sedentary person. For an active CELSS crew member, total daily energy expenditure could be about 600 kcal above the NRC recommendation, so with that diet/exercise regimen, Al would lose weight. Therefore, he would have to consume more food during planetary exploration, and the growth area and power requirements for crop production in a CELSS would have to be revised upward from previous estimates. Since astronauts and cosmonauts are now consuming more than 3000 kcal per day on busy orbital space-flight missions (Ahmed 1992), this scenario is not unrealistic for a CELSS diet and activity schedule on the moon or Mars.

CANDIDATE SPECIES FOR A CELSS VEGETARIAN DIET

CELSS candidate crop species were selected originally for their productivity potential as well as for their ability to provide calories and/or protein for a vegetarian diet (Hoff *et al.* 1982). The "original" macronutrient-providing CELSS crops were wheat (*Triticum aestivum* L.) (Bugbee and Salisbury 1988), white potato (*Solanum tuberosum* L.) (Tibbitts *et al.* 1994), and soybean (*Glycine max* Merr.) (Raper *et al.* 1991).

Table 1 Oxygen consumption and energy expenditure for a 79-kg (174 lb) adult male with a CELSS-compatible daily activity profile (Guyton 1991, McArdle *et al.* 1986).

Activity	Duration	O_2 consumption (liters)		Energy expended (kcal)[b]	
	(h·day^{-1})	(kg^{-1}·h^{-1})	(person^{-1}·day^{-1})	(kg^{-1}·h^{-1})	(person^{-1}·day^{-1})
Textbook value (sedentary)		0.21	398.2	1.05	1990.8
Sleep	8	0.19	117.6	0.93	587.2
Eating/social	3	0.27	63.6	1.34	317.4
Sitting/rest	2	0.29	45.2	1.43	266.0
Office work	4	0.40	126.4	2.00	632.0
Light exercise	2	0.49	76.8	2.45	383.8
Hands-on work	4	0.69	216.8	3.43	1083.6
Heavy exercise	1	0.83	65.5	4.14	327.3
Total activity	24		711.9[a]		3557.3

= 173 W

[a] An O_2-consumption rate of 712 liters O_2·person^{-1}·day^{-1} is equivalent to 28 moles O_2·person^{-1}·day^{-1} at STP.
[b] 5 kcal·(liter O_2)$^{-1}$.

Soon after, sweetpotato (*Ipomoea batatas* Lam.) and peanut (*Arachis hypogaea* L.) were added to the list of candidate species (Hill *et al.* 1989, 1991). Still later, rice (*Oryza sativa* L.) (Volk and Mitchell 1995), cowpea (*Vigna unguiculata* (L.) Walp.) (Ohler and Mitchell 1995), and dwarf brassica (*Brassica napus* L.) (canola) (Frick *et al.* 1994) also were added for flexibility in composing diets. Additional research has been performed with leaf lettuce (*Lactuca sativa* L.) (Knight and Mitchell 1988) and tomato (*Lycopersicon esculentum* Mill.) (McAvoy and Janes 1988) as candidate salad crops to add variety and micronutrients to the CELSS diet.

PROTEIN AND FAT CONTENTS OF CANDIDATE SPECIES AND OF THE CELSS DIET

The Recommended Dietary Allowance (RDA) suggests 0.8 g protein$\cdot$(kg body wt)$^{-1}\cdot$day^{-1} for males between 25 and 50 years of age (NRC 1989), which translates into 63 g protein$\cdot$day^{-1} or 8.7% of Al's recommended daily caloric intake. However, the Food and Nutrition Board of the U.S. NRC allows an upper limit of protein intake at twice the RDA. Given the negative nitrogen balances experienced by astronauts under spaceflight conditions (Lane and Gretebeck 1994), composing diets of 15% protein or higher for long duration planetary missions under hypogravity conditions may be a prudent thing to do. In fact, the protein intake of men 19 to 50 years of age in the U.S. averages 16.5% of energy intake (USDA 1986). Although there is no formal RDA for fat intake, various dietary guidelines recommend that total dietary fat intake be limited to 30% or less of total energy, and that saturated fat be less than 10% of total energy (USDA 1995). The remainder (and majority) of macronutrient calories are derived from carbohydrate (CHO). Many vegetables are rich in complex carbohydrates, low in saturated fat, and contain no cholesterol. Cereal grains and legume seeds typically comprise the staple basis of vegetarian diets balanced for protein amino acids (Pennington 1994). Even though soy protein approaches a complete amino acid profile such as that from animal sources (Pennington 1994), total dietary protein is too high when soybean is used as the sole source of "balanced" protein (Volk and Cullingford 1992).

Soybeans grown in the field typically have a protein content averaging about 34% of seed dry weight (Haytowitz and Matthews 1984). However, when grown hydroponically under nitrogen-rich conditions, the protein content of

Table 2 Macronutrient composition of CELSS candidate crop species grown in controlled environments (Nielsen *et al.* 1996).

Species	Content in edible portion (% dwb)			Energy Content
	Protein[a]	Fat	Carbohydrate[b]	(kcal$\cdot$100 gDW^{-1})
Canola	29.7	33.8	32.0	551.0
Cowpea	28.3	1.3	65.7	387.7
Peanut	29.3	49.5	18.5	636.7
White potato	17.9	1.8	73.8	383.0
Rice	17.0	3.1	78.0	407.9
Soybean	53.4	19.6	20.7	472.8
Sweetpotato	3.3	2.0	93.4	404.8
Wheat	24.4	1.4	72.1	398.6

[a] Protein content determined by total N$\times$6.25 for canola, cowpea, white potato, rice, soybean, and wheat. Note that not all N is protein for some species, especially under controlled environment conditions. Method for true total N is a modified Kjeldahl procedure, as described by McKeehen *et al.* (1996). Protein content of all other samples was determined by standard Kjeldahl procedure.

[b] Carbohydrate values are calculated by difference: % carbohydrate = 100% − (% protein + % fat + % ash).

soybean seeds has been found to be as high as 53% (Table 2). The protein content of crops storing protein as a major macronutrient generally is enhanced by the high availability of nitrogen in hydroponic culture (McKeehen *et al.* 1996, Mitchell *et al.* 1996). Protein content of other legumes, cereals, and white potato also is higher when grown in controlled environments (Table 2) than in the field (Haytowitz and Matthews 1984, Watt and Merrill 1963). Peanut and canola are lower in protein but higher in fat than is soybean, so they lend flexibility in proportioning these two important macronutrients. Cowpea is the only low-fat legume presently in the CELSS diet arsenal, which may give it utility for extruding various pasta products from legume meal and cereal flour (Fu *et al.* 1995). Since the protein of non-soybean legumes is "incomplete" (Pennington 1994), peanut and cowpea protein can be used only in combination with cereal protein (wheat and/or rice) to provide a complete essential amino acid profile for humans. Sweetpotato is the only CELSS candidate crop that is not enhanced in protein content when grown in controlled environments (Table 2). This makes sweetpotato a valuable crop for completing the caloric balance of CELSS vegetarian diets without significantly enhancing the protein (or fat) contents of those diets. However, productive sweetpotato cultivars need to be selected or bred for low β-carotene content to avoid vitamin A toxicity in monotonous vegetarian diets. Furthermore, nitrogen nutrition protocols need to be developed for white potato that prevent accumulation of undesired protein content in tubers without compromising crop productivity.

PROPORTIONING EDIBLE BIOMASS FOR DIFFERENT DIET STRATEGIES

The diet components summarized in Table 3 demonstrate that a variety of protein and fat contents can be achieved for diets of the same total caloric value using only five or six CELSS candidate species. Three different dietary goals were developed using similar components in different proportions: Diet I achieved the RDA for balanced (15%) and total protein (15 to 18%) but was at the lower end of fat recommendations at 21% of total calories. Remaining calories were provided by complex CHO. Diet II places fat content midway in the RDA range at 26% of calories but increases total protein to 21% calories. These increases were at the expense of carbohydrate, which was reduced to 53% of total calories to keep the overall diet iso-caloric at 3557 kcal$\cdot$person$^{-1}\cdot$day^{-1}. Diet III is in line

Table 3 Variations on 3557 kcal$\cdot$day^{-1} vegetarian diets using different combinations of crop species.

Diet no. Component (% total kcal)	Percent of food component calories provided by the given crop							
	Canola	Cowpea	Peanut	White potato	Rice	Soybean	Sweet-potato	Wheat
I								
Protein (16)	5.20	–	19.28	–	57.78	14.46	3.36	–
Fat (21)	10.41	–	57.83	–	18.70	9.45	3.61	–
CHO (63)	1.45	–	3.17	–	69.04	1.46	24.88	–
II								
Protein (21)	15.37	–	18.35	10.96	–	–	0.32	54.99
Fat (26)	33.05	–	58.52	2.07	–	–	0.39	5.97
CHO (53)	6.74	–	4.71	18.38	–	–	3.97	66.20
III								
Protein (23)	–	4.39	20.30	11.64	13.18	48.33	2.15	–
Fat (29)	–	0.34	60.10	2.05	4.20	31.02	2.29	–
CHO (48)	–	4.83	6.07	22.74	28.60	8.86	28.87	–

with more liberal fat recommendations at just under 30% of total calories. The penalty for achieving this level of fat is that total protein was raised concomitantly to 23% of total calories. Care was taken to ensure that balanced protein (i.e., from soybean alone and/or from cereal+non-soy legume in a 3 : 1 ratio of protein calories) was maintained at 15% of total calories for each diet strategy (Lappe 1971). Each diet formulation was initiated with sufficient peanut to approach the final desired content of fat, although peanut was not used as the sole source of fat. Of the fat-providing candidate species, the (caloric) ratio of fat to protein was highest for peanut (1.7 : 1), moderate for canola (1.1 : 1), and lowest for soybean (0.4 : 1). Therefore, the strategy for each diet formulation was to get a good start on the desired fat content with peanut, then use cereal in a 3 : 1 ratio of cereal-to-legume protein calories to complement the amino acids of peanut protein. Then, either soybean alone and/or cowpea plus rice or wheat was used to top off balanced protein at 15% of total calories. Protein in excess of 15% was a consequence of using other crops to bring fat or carbohydrate content to desired levels or total calories to 3557 $kcal \cdot person^{-1} \cdot day^{-1}$. Due to its very low protein and fat contents (3.3% and 2.0%, respectively), sweetpotato was effective in rounding out total calories with its very high carbohydrate content (93%). Although none of these CELSS candidate crop species represents a perfect source of complete and well proportioned macronutrients when used alone, different combinations provide great latitude in composing a variety of diets. Neither wheat nor soybean are absolute requirements for balancing CELSS diets with respect to macronutrients or calories. Future research should determine how to precisely manipulate and control macronutrient contents of CELSS crops in controlled environments, giving even greater flexibility in custom-designing healthful vegetarian diets for planetary habitation, as well as for personal preference.

GROWTH AREAS FOR MACRONUTRIENT-BALANCED DIETS

If the food ingredients for each CELSS diet strategy are totaled, they range from 775 to 804 g DW edible $biomass \cdot person^{-1} \cdot day^{-1}$, depending on the relative proportions of fat, protein, and carbohydrate used (Table 4). Fat, having the highest caloric density (9 kcal/g DW), reduces the amount of edible biomass needed to provide calories as its proportion increases in the diet. Dividing each ingredient amount by the nominal yield rate of that crop, either already established,

Table 4 Requirements for crop yield, diet ingredients, and growth areas for different crop combinations to supply 3557 $kcal \cdot day^{-1}$ diets for different diet scenarios.

Crop	Edible yield rate ($gDW \cdot m^{-2} \cdot day^{-1}$)	Ingredient requirement ($gDW \cdot person^{-1} \cdot day^{-1}$)			Growth area ($m^2 \cdot person^{-1}$)		
		Diet scenario			Diet scenario		
		I	II	III	I	II	III
Canola	20	25	99	–	1.2	5.0	–
Cowpea	20	–	–	31	–	–	1.6
Peanut	15	96	120	140	6.4	8.0	9.3
White potato	25	–	117	132	–	4.7	5.3
Rice	25	495	–	157	19.8	–	6.3
Soybean	20	40	–	183	2.0	–	9.2
Sweetpotato	20	148	20	132	7.4	1.0	6.6
Wheat	40	–	431	–	–	10.8	–
Total	–	804	787	775	36.8	29.5	38.3

conservatively projected, or, in the case of wheat, backed off from the maximum achieved, gives a realistic total growth area for each mix of crops. As environmental optimization work progresses, the anticipated total growth area required for CELSS crops will shrink below the 30 to 38 m^2 estimated from this analysis. The lowest cropping area requirement, for diet scenario II, for example, results from the high edible yield rate of wheat used as the source of cereal protein and calories in that diet. Wheat productivity has been maximized more than that of other CELSS candidate species because of its ability to tolerate high light input. Nevertheless, there remains considerable potential to further improve the yield rate of other candidate species. On the other hand, losses of edible biomass during food processing (as waste) plus bioavailability limitations of the human digestive system will push the total growth-area requirement even higher than present estimates. If we liberally estimate that no less than 95% of total edible crop biomass will be retained during food preparation, and that 90% of all macronutrients are bioavailable to humans across all (heat-processed) diet scenarios, then the cropping areas must be corrected upward to 43, 34, or 45 $m^2 \cdot person^{-1}$ for diet senarios I, II, and III, respectively. Addition of small amounts of salad (lettuce, tomato, sprouts), vegetable (e.g., broccoli, cowpea and sweetpotato leaves), and herb (onion, garlic, basil) crops will be important for psychological augmentation of the diet (i.e., variety, texture, aesthetic, and organoleptic qualities) and would further tweak cropping area requirements slightly upward. In many cases, only one $plant \cdot person^{-1} \cdot day^{-1}$ might be required (e.g., lettuce), or a single plant might serve an entire CELSS crew for months (e.g., tomato, basil).

POWER/ENERGY REQUIREMENTS FOR CONTROLLED ENVIRONMENT CROP PRODUCTION

Another important consideration for sustaining a CELSS in space will be the electrical energy required to energize plant-growth lamps and/or temperature-control systems for crop production. Electrical power draw by contemporary plant-growth chambers has been measured at the connected load at the Kennedy Space Center and at Purdue University. Power draw per unit growth area (2 to 3 $kWatt \cdot m^{-2}$) is not typically high enough to drive maximum crop productivity, but is of a level adequate to support moderate productivity of CELSS crops in commercial growth chambers. The power requirement for each crop in a given diet scenario depends not only on lamp wattage and geometry of irradiation but the area of crop canopy grown, the productivity of that canopy, and the photoperiod under which the crop is grown (Table 5). Wheat is a major consumer of electrical energy (as in diet II) because it is grown under continuous high irradiance lighting. Rice also requires substantial energy because its present productivity rate is only moderate (requiring more growth area), but still uses less total energy than wheat because its photoperiod is only 12 h/day (Goldman and Mitchell 1995). The present energy burden needed to produce crops in controlled environments will decline for each crop as we learn where and when to apply the right amount of light, and as we develop more efficient lamps with which to irradiate crops. For example, plant-growth lamps in common use range from 10% to less than 30% efficiency in converting electrons to photons (Mastalerz 1977). Planophile (horizontal-leaved) dicotyledonous crops that mutually shade lower leaves in closed canopies might be more efficiently lighted with low irradiance intracanopy lighting systems than with traditional high irradiance overhead lighting systems (Ohler and Mitchell 1995).

Table 5 Power and energy requirements to provide different 3557 kcal·person^{-1} diets for a reference person in a CELSS. Growth area data for each crop and diet scenario from Table 4 were used to help calculate power and energy requirements.

Crop	Power (kWatt·person^{-1})			Photoperiod (h·day^{-1})	Energy (kWatt-h·person^{-1})[b]		
	Diet scenario				Diet scenario		
	I	II	III		I	II	III
Canola	2.4	10.0	–	16	38	160	–
Cowpea	–	–	3.2	8	–	–	27
Peanut	12.8	16.0	18.6	12	154	192	223
White potato	–	9.4	10.6	12	–	113	127
Rice	39.6	–	12.6	12	475	–	151
Soybean	4.0	–	18.4	12	48	–	221
Sweetpotato	14.8	2.0	13.2	12	178	24	158
Wheat[a]	–	32.4	–	24	–	778	–
Total	73.6	69.8	77.2	–	893	1267	907

[a] Total electrical input power/area for irradiated wheat is 3 kWatt·m^{-2}, whereas that for the other crops is 2 kWatt·m^{-2}.

[b] Daily energy expenditure for each crop and for the total of all crops was integrated over the photoperiod. There actually would be an additional, low level baseline energy expenditure associated with maintaining chamber conditions in darkness that is not included in these calculations.

The instantaneous power requirement to produce CELSS crops ranges from 70 to 77 kWatts·person^{-1}, depending on the diet scenario (Table 5). This power might be provided by a nuclear reactor and/or by arrays of photovoltaic cells. In space near Earth, the solar constant is 2 langleys·min^{-1}, which is equivalent to about 2 cal·cm^{-2}·min^{-1} or 1360 Watts·m^{-2} (Nobel 1983). Assuming 15% solar conversion efficiency of durable photovoltaic cells, each m^2 of solar cell could generate as much as 204 Watts of electrical power. To satisfy the power requirement to grow crops for diet sceanrio II (70 kWatts·person^{-1}), 343 m^2 of photovoltaic sensor area would be required. As the efficiency of durable photocells improves, these figures also will decline. The total daily energy burden to produce a balanced vegetarian diet from CELSS crops hovers around 10^3 kWatt·h for all diet scenarios.

THE IMPORTANCE OF HARVEST INDEX

Most CELSS candidate crop species providing major macronutrients for vegetarian diets have a harvest index (i.e., proportion of edible biomass) less than 50%, which is the factor most limiting net productivity in a CELSS (Bugbee 1992). The nonedible crop residue will consume just as much O_2 and energy during reoxidation to CO_2, water, etc., as were liberated during photosynthesis in the first place (Mitchell 1994). The only useful biomass produced in a CELSS will be edible biomass, plus non-edible biomass that can be rendered edible. If the extra O_2 required to oxidize non-edible crop biomass that is formed in a CELSS is not brought along and stored initially, then the crop canopy area would have to be further revised upward, to an average of 78 m^2·person^{-1} for all diet scenarios in order to provide additional O_2 for waste biomass oxidation during the first cropping cycle. It clearly would be preferable to initially "charge" the CELSS system with sufficient stored O_2 to avoid unnecessary cropping area. As food-process and waste-degradation protocols become more defined, their power and energy penalties need to be added to those for crop production.

BALANCED VEGETARIAN DIETS ARE THE DRIVERS FOR CELSS

CELSS is unique among regenerative systems in that it is the only life-support scenario to include production of human food from renewable resources. Photosynthetic higher plants simultaneously revitalize atmosphere and purify water while producing edible biomass, so they comprise a critically important, integrated life-support component for humans. Production of edible biomass for distant, long-duration space destinations is the major driver justifying CELSS. As the sole or major source of food in a CELSS, it is imperative that vegetarian diets be balanced nutritionally, especially with respect to major macronutrients. Dietary supplementation with micronutrients and vitamins is feasible for small crew sizes and limited duration missions. However, nutritional balance should be paramount in defining the operational parameters for a CELSS, including area, volume, mass, power, and labor. This analysis emphasizes how realistic human activity and dietary requirements should drive crop selection, cropping proportions, and major resource inputs to the crop production sub-system. It also suggests that a human-centered view of CELSS should drive the design of its subsystems as well as their integration.

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